NASA's Future Missions and Thermal Protection System (TPS) Needs for Lunar and Planetary Exploration

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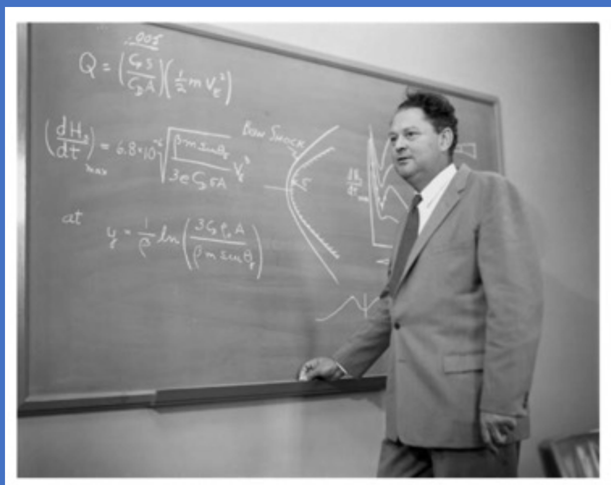
AM-TPS Workshop | Houston, TX | March 28, 2022

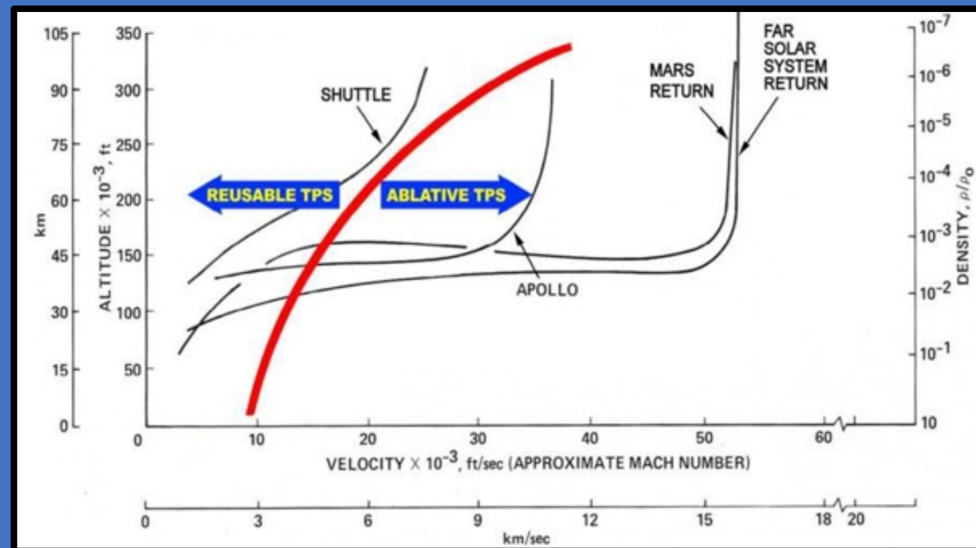
Introduction and Outline

- NASA missions are often one-of-a-kind and post-Apollo new entry vehicle mission cadence has been low
- NASA depends on aerospace prime contractors. When a vehicle provider needs new TPS, technology developed by NASA is transferred to the prime or sub-contractors
  - NASA maintains a core in-house expertise to develop NASA-unique TPS and manage the mission, especially aspects of Entry, Descent and Landing (EDL)
- With emerging Commercial Space, NASA needs to continue to be both a smart buyer as well as develop technologies that benefit the broader commercial space market needs
- This workshop is a prime example of asking “What should be NASA’s role in the technology development that combines additive manufacturing and TPS?” to benefit not only future NASA missions, also help other Government agencies and Commercial Space
- This opening talk will focus on NASA missions, past, present and future, with a focus on their thermal protection systems.

Planetary Missions: Blunt Aeroshells and Ablative TPS



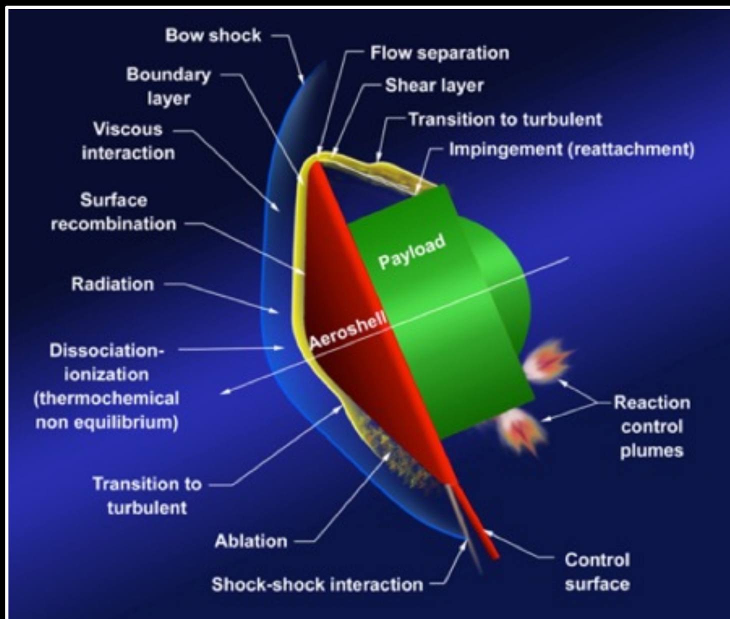
Harvey Allen (1952), Blunt-body Concept
for surviving Hypersonic Reentry (Photo: NASA)

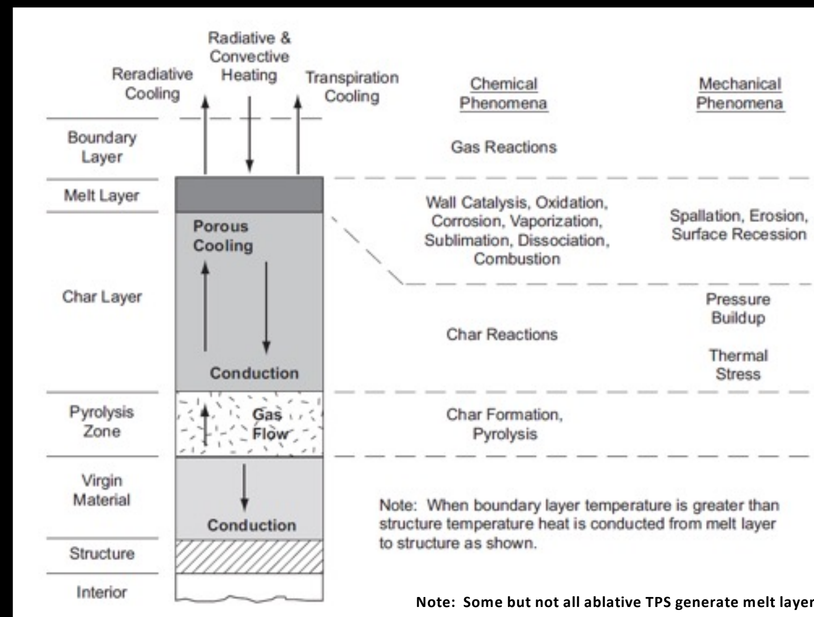


- Entry at higher speeds dictates:
  - Blunt aeroshell shape and the need for ablative TPS – Harvey Allen established this in 1952
  - Apollo missions were successful due to ablative TPS on blunt aeroshell
- The plot shows Velocity-Altitude profile comparison - Shuttle Orbiter (Reusable TPS) and Lunar/Planetary entry missions needing ablative TPS.

Complex Physics Surrounding Blunt Aeroshells and Ablative TPS - A Quick Primer

Complex Aerothermal Flow-Physics during Hypervelocity Entry

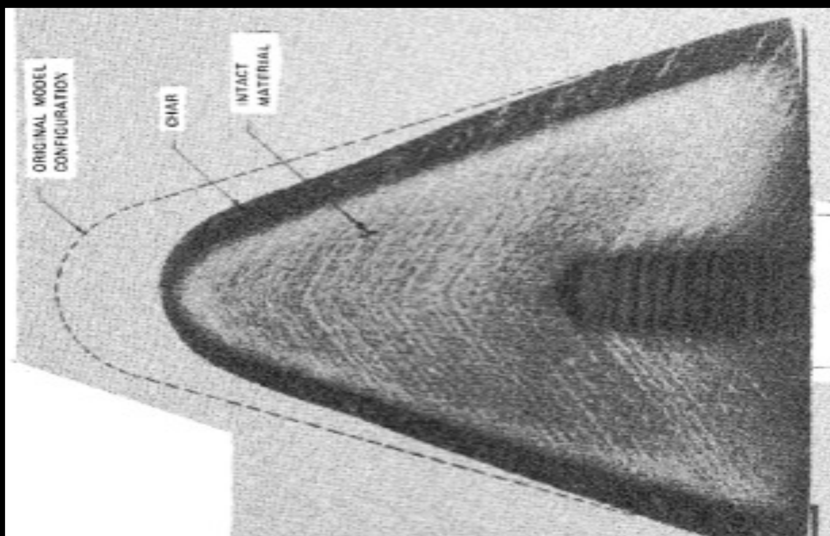




Most planetary entry missions will use a single, higher density ablative TPS for the heatshield acreage and one or more lower-density ablative materials for the backshell

- Apollo used the same ablative TPS for both the heatshield and backshell
- Most other probes use different TPS to cover the heatshield and the backshell

Dealing with Heat: Ablative Thermal Protection System



From: G.W. Sutton AIAA 82-4038.

Post Arcjet Test Article – Wrapped Silica-Phenolic
1 inch base (1958)

Ablative TPS Material:

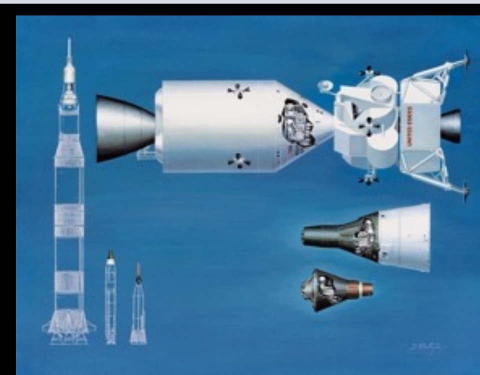
- **Rejection through re-radiation:** Forms good char to re-radiate most of the heat (90 % - 95%) – First line of heat rejection
- **Convection:** Takes the heat away from the body; resin decomposes into gaseous products and takes the heat away through the porous char
- **Insulation:** delay the heat penetration as long as possible
- **Robustness (no failure):** does not excessively melt and flow, spall, or flake away

Mercury, Gemini (50’s and 60’s):

Apollo (61 – 72)
16 Un-crewed and 11 Crewed flights
3.91 m heat shield – Peak heating ~ 600 W/cm2

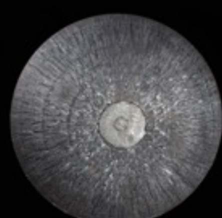
Gemini (61-66)
2 Un-crewed and 10 crewed flights
3.05m heat shield – Peak heating ~ 60 W/cm2

Mercury (58 –63)
20 Un-crewed and 6 crewed flights
1.9 m heat shield – Peak heating ~ 50 W/cm2



1950	1960	1970	1980	1990	2000	2010	2020

President Kennedy's announcement May 25, 1961



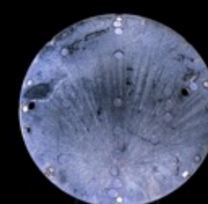
HS - Fiberglass-phenolic shingles

Retro rockets attached to the heat-shield.

Water impact landing

Landed with heat shield intact due to recontact issues

Heatshield center plug kept falling off on most crewed flights



HS - Fiberglass honeycomb filled with silicone elastomer with room temperature cure

Honeycomb bonded to the structure allowed attachment verification

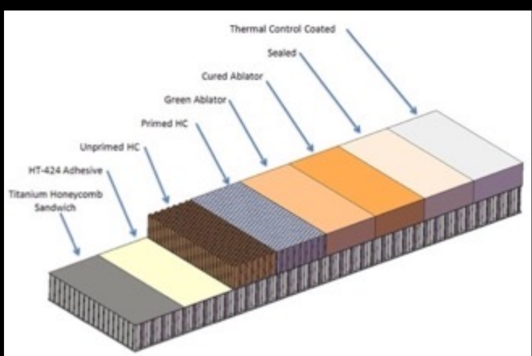
Virgin white surface turns black as a result of charring.

Glass forms at the surface during heating and melt flow

Images: NASA

Fun Fact : In the Times Past When there was no Internet Mercury Capsule Toured the World - Both in Space and on Earth

Apollo (1961 - 1972) 16 Un-crewed and 11 Crewed flights 3.91 m heat shield – Peak heating ~ 600 W/cm2



- Avco Corp. developed the ablative material, and the manufacturing process in 3 years.
- Avcoat 5026-39G. Epoxy-novalac resin reinforced with quartz fibers and phenolic micro-balloons in a phenolic honeycomb
- Avco invented a way to fill each of the cells by hand and developed repair procedures. 360,000 cells (heatshield and backshell). On average, 30,000 (10%) cells were defective and repaired
- The phenolic honeycomb is first bonded to the structure, then filled with ablative compound through a dispenser (like a caulking gun)
- Qualified for In-space thermal environment of (-260^{0}F to + 250^{0}F)
- Impact of Micro-meteoroid damage was assessed
- Forebody penetration (Compression pad) required integration of fiber-glass phenolic compression pads with heatshield. Backshell has numerous cutouts.

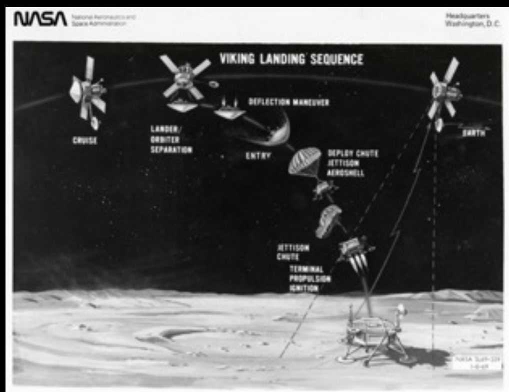
Photo Credits: Smithsonian collection/Textron/NASA

Apollo (1961 - 1972) – AVCO Corp Movie Now Available: "1000 Seconds to Home: Apollo Heat Shield"

View the full movie at
https://www.youtube.com/watch?v=64UM3CUqSfg

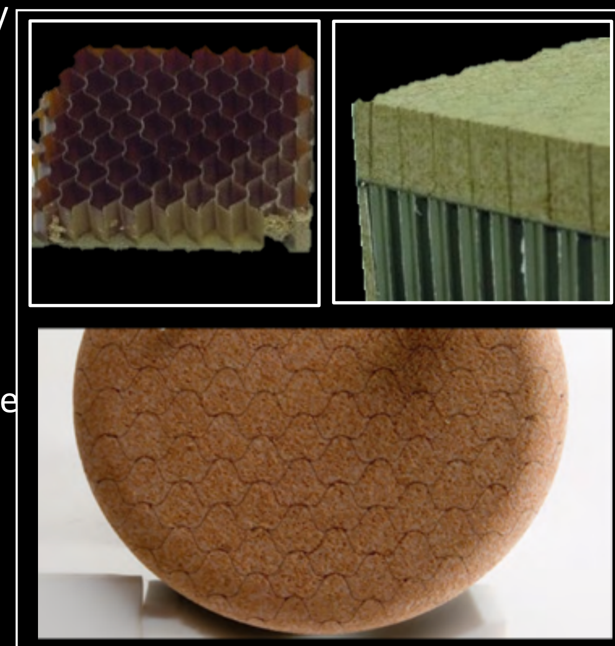
Automation was used to perform final machining!

Viking Landers (1976) 2 Landers – Delivered from Orbit 3.5m heat shield – Peak heating ~ 26 W/cm²



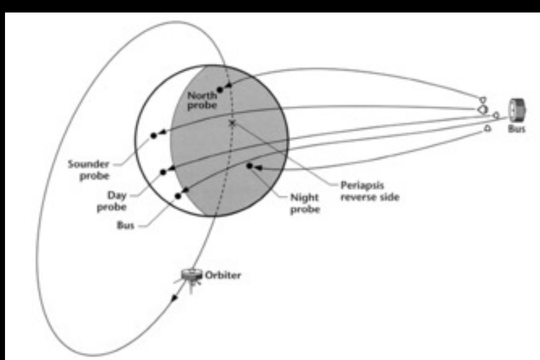
Pictures Credit: NASA and Lockheed Martin

- Super-Lightweight Ablator - SLA-561V
  - Apollo heatshield too heavy for Mars entry
  - Good insulator and lighter (< 50% the density of Avcoat)
- Developed (late 60's) by Martin Marietta*
  - Made of ground cork, silica and carbon fibers, silica and phenolic micro-balloons and silicone.
  - Uses honeycomb to bond to the structure and hold the ablative material. The ablative material was hand-packed, seamless
- Manufacturing
  - Hand packing. Could not use "gunning."
- Testing showed robust performance
  - In-space environment, vibro-acoustics, thermo-structural, thermal
- Planetary protection requirement



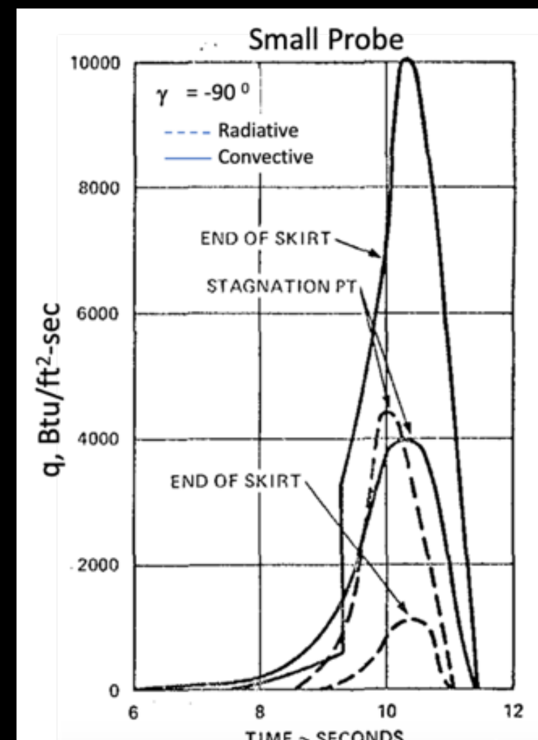
*Martin Marietta became Lockheed Martin

Pioneer-Venus (1978) 3 Small (0.76 m) and 1 Large (1.52 m) Probes
Peak design heat flux 10 kW/cm^2 at 10 atm. pressure



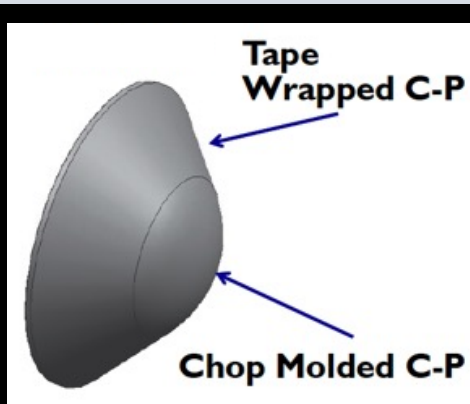
Pioneer-Venus:

- 4 probes (3 small and one large)
- Shock layer radiation dominated (much more severe than Apollo)
- Combined convective and radiative - an order of magnitude higher than Apollo
- Ablative TPS material to handle severe entry conditions for the Venus
  - Reflective material (Teflon) considered but rejected
  - Phenolic-Nylon vs Carbon-Phenolic evaluation
  - Carbon-Phenolic tested in air and CO_2
- GE (Valley Forge) developed high density carbon phenolic, two-piece, heat shield (1975)
  - Two different manufacturing, nose and frustum with Chop-Molded and Tape-Wrapped carbon phenolic
  - Tape-wrapped derived from DoD



Images: NASA

Carbon Phenolic (C-P) Heatshield
Manufacturing Aspects of Chop Molded and Tape Wrapped



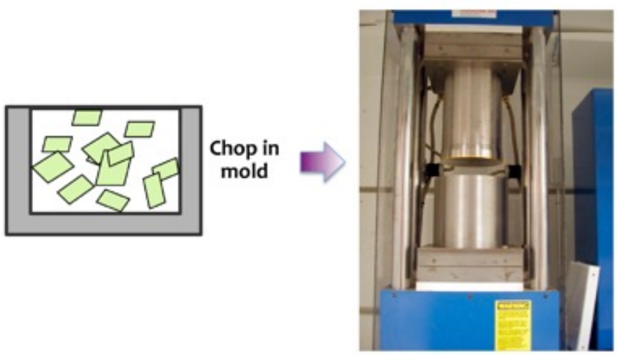


Figure 4. Process for fabricating and curing chopped-molded carbon phenolic showing molding compound in a mold and a hot press, which is used for curing the part

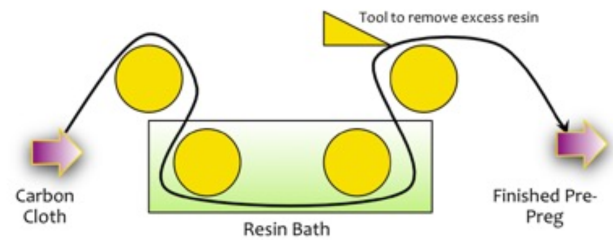


Figure 2. Process of infiltrating carbon cloth with phenolic resin to create prepreg

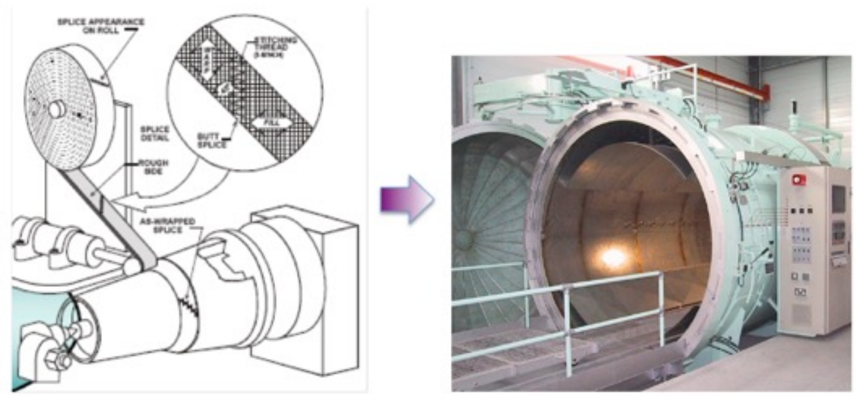
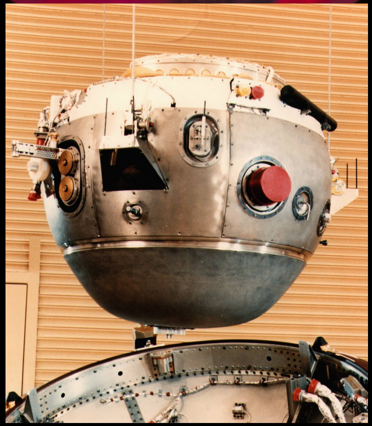
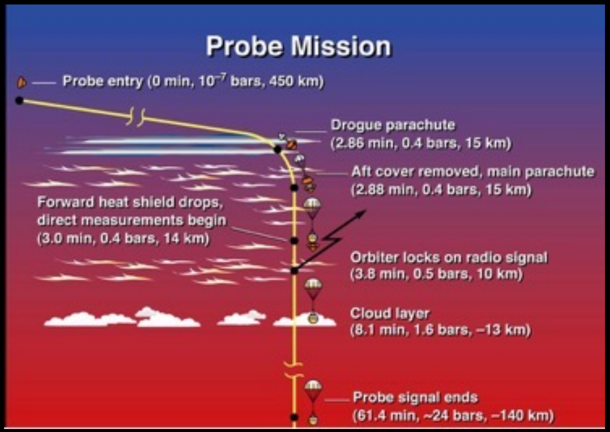


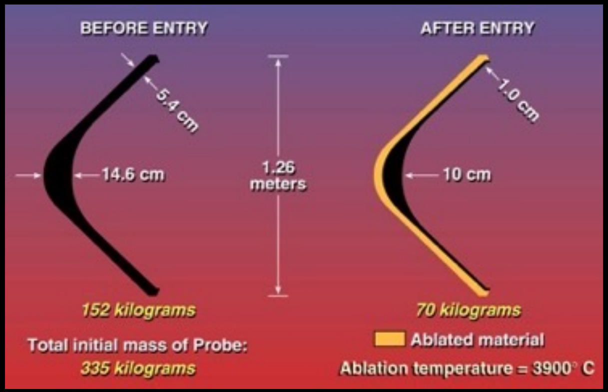
Figure 3. Process for fabricating and curing tape wrap carbon phenolic showing tape being applied on a mandrel and an autoclave, which is used for curing the part

Galileo (1995) - Single Probe Entry at 47.4 km/sec
Peak conditions (30,000 W/cm2 and 7.3 atm)



- **Heating at ~ 49 km/sec entry – extreme**
- Peak heat-flux exceeded the heating at the nose tip of a ballistic missile and the radiative heating from a thermonuclear explosion **combined.**
- GE Carbon Phenolic (2 piece) chop molded and tape wrapped heat shield manufacturing adopted from successful P-V experience.
- Heat shield mass was 50% of entry mass.
- Recession sensors in the heat shield provided data
- In 15 sec., 50% of the heat shield ablated
- Margined design proved to be non-conservative on the shoulder – near failure





Images: NASA

Summary (1960 – 1980): NASA Missions and Ablative TPS

Avcoat → Apollo (61 – 72)

Gemini (61-66)

Mercury (58 –63)

1950	1960	1970	1980	1990

SLA → Viking (69 -76)

SLA: Super Lightweight Ablator

P-V (68 -78)

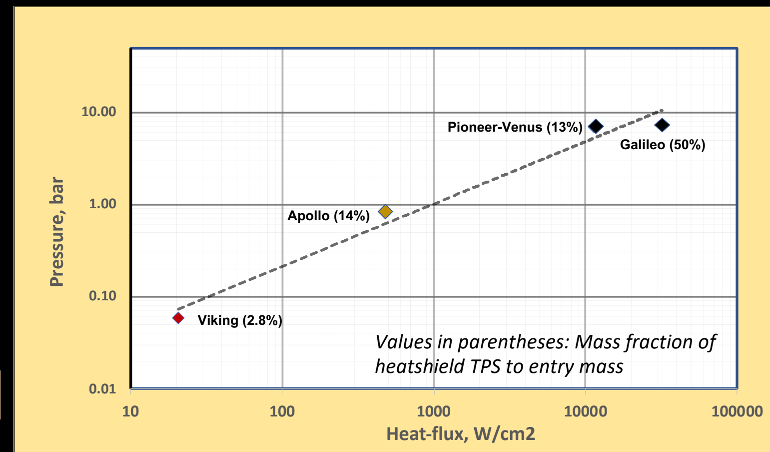
Galileo (75 – 89 - 95)

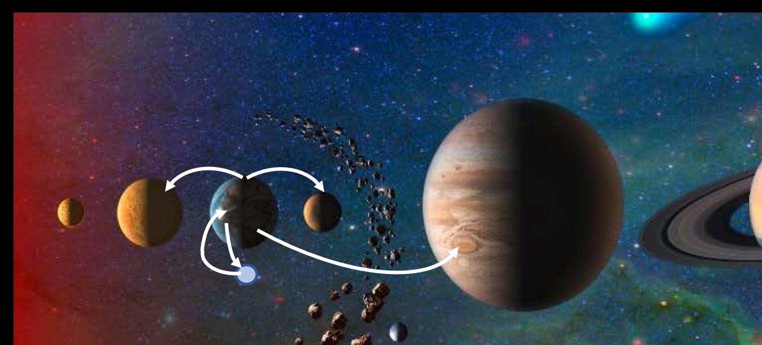
CMCP TWCP → P-V, Galileo

Ablators (1960 – 1980)

1. **Avcoat 5026-39 G**
2. **SLA-561V**
3. **Carbon Phenolic**

CWCP: Chop Molded Carbon Phenolic
TWCP: Tape Wrapped Carbon Phenolic

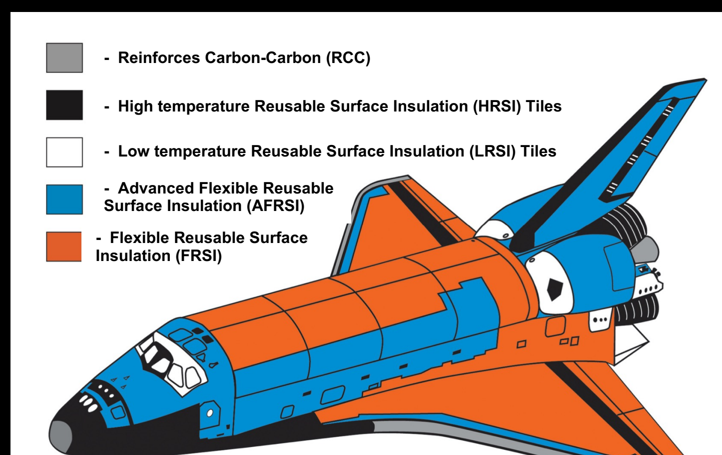




Space Shuttle Orbiter (1980 - 2010): Reusable TPS

Space Shuttle System
(1969 – 1981) ->2011

1950	1960	1970	1980	1990	2000	2010	2020



nasa.gov

Pathfinder (2.65m) , Stardust (0.83m) and Genesis (1.5m) Smaller “Faster, Better, Cheaper” Missions of 1990’s

Pathfinder Aeroshell Mars entry at 7.5 km/s (7/4/1997)

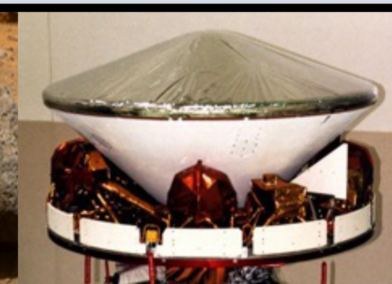
- Peak heat flux of 100 W/cm2 at 0.2 bar pressure
- SLA-561 V had to be recovered to ensure performance reproducibility

Stardust – Sample Return Capsule Earth entry at 12.5 km/s (1/15/2006)

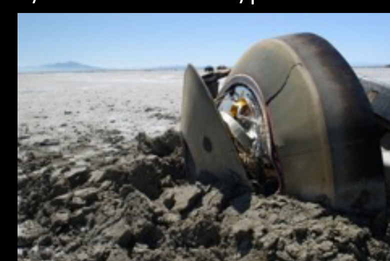
- Peak stagnation conditions 1200 W/cm2 and 0.275 atm.
- Heatshield - New lightweight TPS – PICA (Phenolic Impregnated Carbon Ablator)
- FMI’s FiberForm™ was cast in the shape of the heatshield as single piece and resin infused, machined and bonded.

Genesis – Sample Return Capsule Earth entry at 11 km/s (9/8/2004)

- Peak heat-flux of 700 W/cm2 and pressure < 0.3 atm.
- PICA could not be scaled in time for Genesis and LM working with C-CAT used ACC-4 (Advanced Carbon-Carbon) with FiberForm™ as insulation.

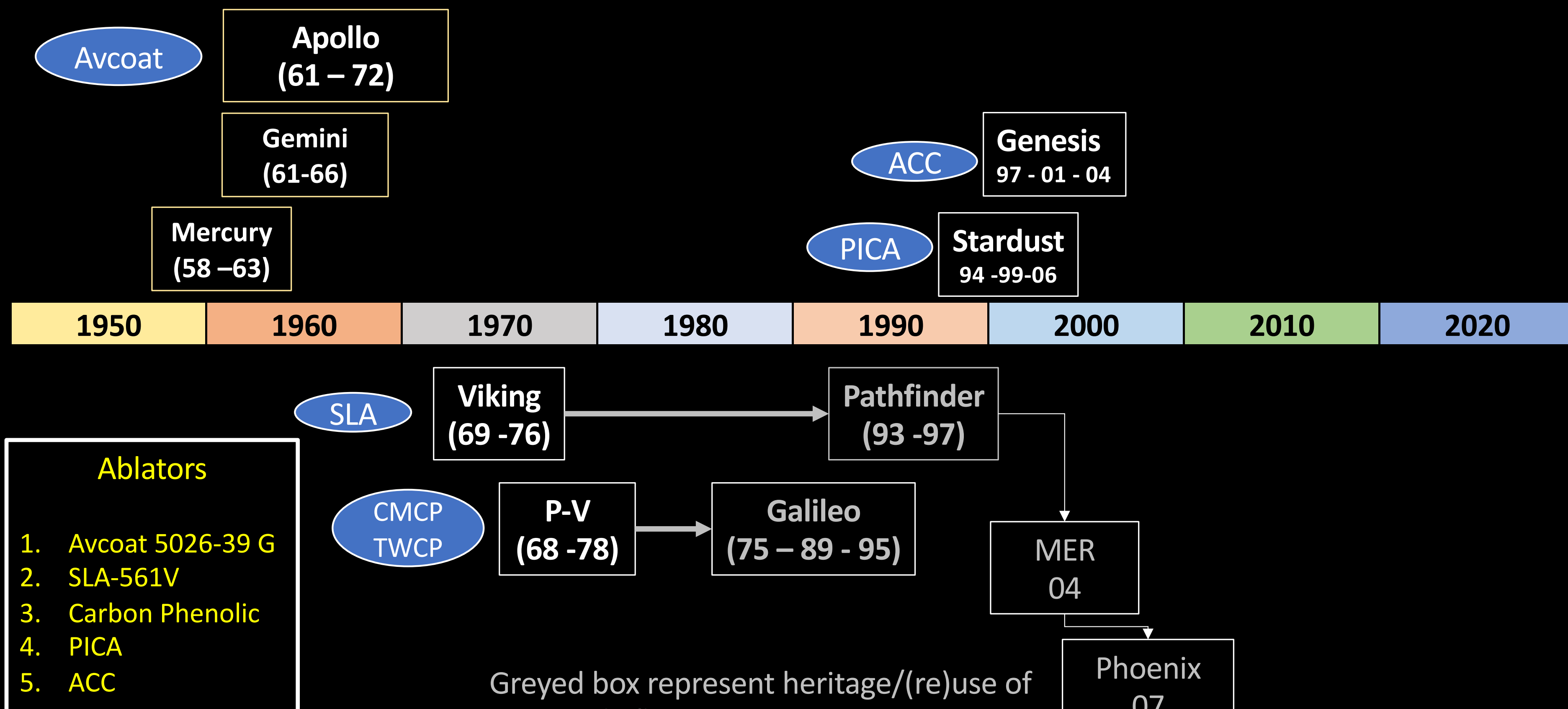



https://www.jpl.nasa.gov/who-we-are/media-information/press-kits

https://www.jpl.nasa.gov/news/press_kits/genesisreturn.pdf

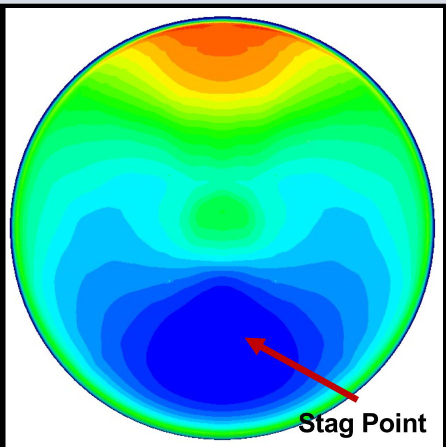
History of Ablators for NASA Missions (2000 - 2010):



Greyed box represent heritage/(re)use of previously flown TTPS

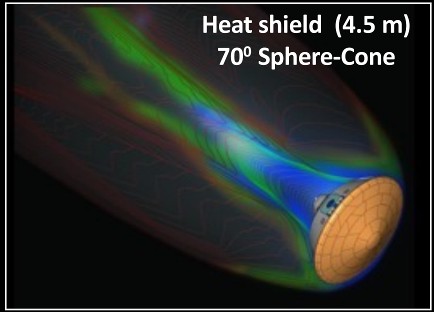
Mars Science Laboratory (MSL) (2005 – 2011)

4.5m dia. – Heat flux - Designed ~ 300 W/cm^2 ; Flight ~ 100 W/cm^2

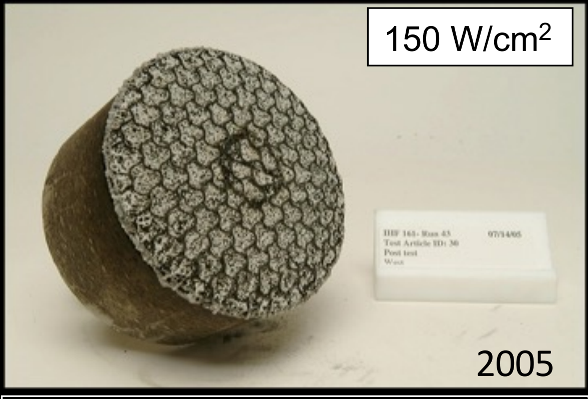


Heatshield Aerothermodynamics Requirements in 2007 at Max. Heat Flux Location	
Requirement	Value
Max. q_w (W/cm^2)	272
Max. τ_w (Pa)	639
Max. p_w (atm)	0.280
Max. Q_w (J/cm^2)	7588

- Mars Science Laboratory – Largest heat shield to Mars - (Launch Sept '09)



- (2005 – 2007): Mass "grew", geometry changed, velocities increased
- Flow on the leeward side predicted to be turbulent
- Conditions were no longer moderate (~2.5x previous Mars missions), especially shear



Orion SLA-561V testing (2007) revealed failure mode - wedge configuration testing at MSL relevant conditions

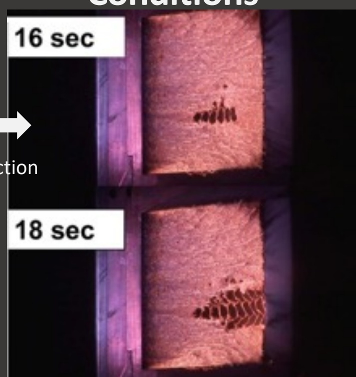
Photos courtesy of Robin Beck and Helen Hwang (NASA)

Mars Science Laboratory (MSL) - Switched from SLA-561V to Tiled PICA in 2008 due to Failure of SLA-561 V

- **SLA-561V was an option evaluated by Orion (LEO)**
- **Failure mode discovered and reported to MSL in 2007**
- **MSL performed further testing and observed failure behavior. Reasons not fully understood.**

SLA Failed – Wedge Under Moderate Conditions

Flow direction



SLA Failed - Swept Cylinder (June 2007) in 4 sec under Moderate Conditions

Flow direction

PICA Swept Cylinder well behaved

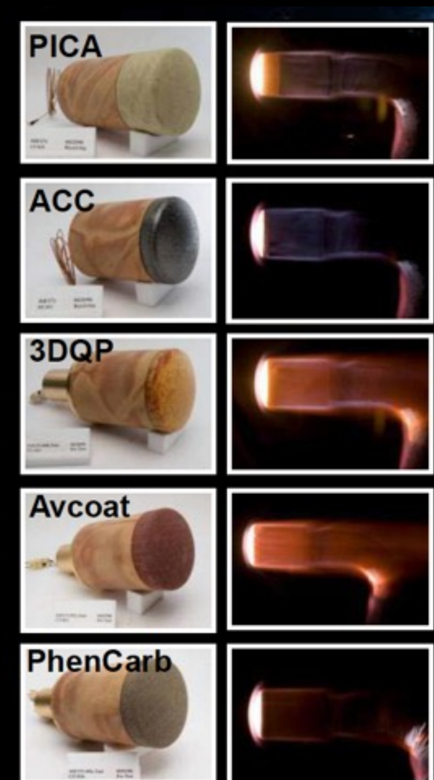
PICA tiles with RTV gap-filler
Wedge Tests

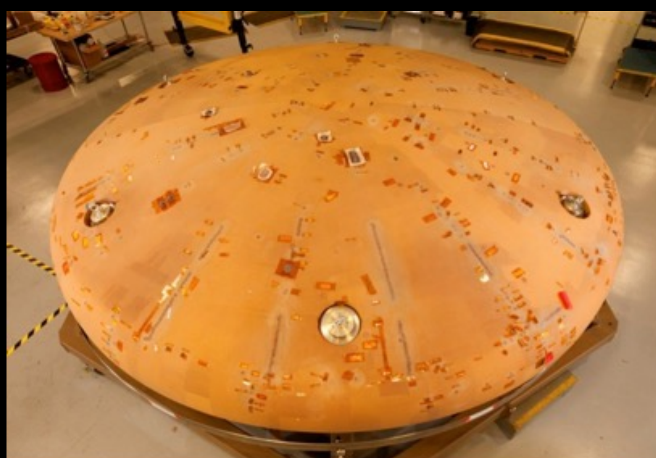
4.5-m diameter tiled ablative heatshield (with in-depth instrumentation!)

Launched in December 2011 – Successfully Delivered Curiosity on August 6, 2012

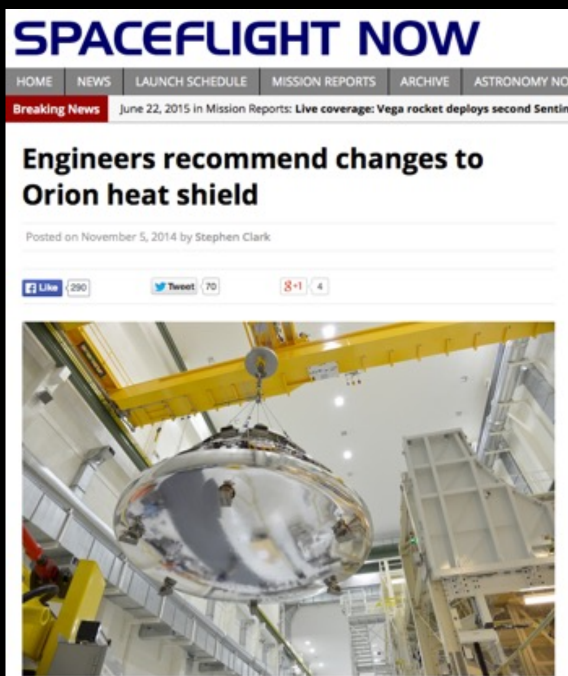
Orion Heat-shield Development (2005 – 2025) and EFT-1 (2009 – 2014) (5 m dia., seamless Lunar and LEO capable)

- Advanced Development Project for TPS (2005 – 2008)
  - A number of TPS at various levels of TRL were evaluated for LEO return only and for LEO and Lunar Return
  - In the end, Avcoat was selected
- Orion EFT1 (2009 – 2014) Avcoat™ 5026-39 HC/G (Honeycomb-Gunned) – 300,000 cells





Post EFT1 Flight Test –Changes to Heat Shield (2015)
Drivers: Cost and Schedule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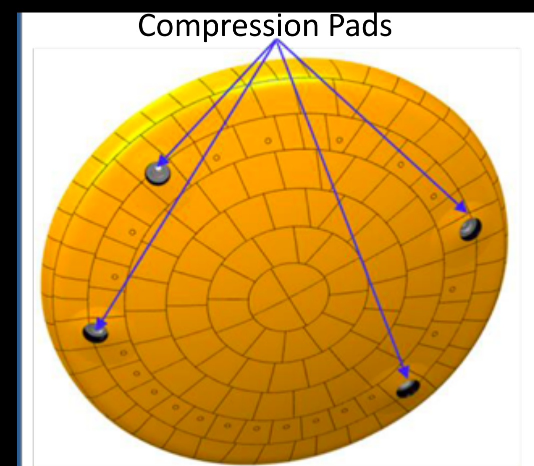
Engineers recommend changes to Orion heat shield

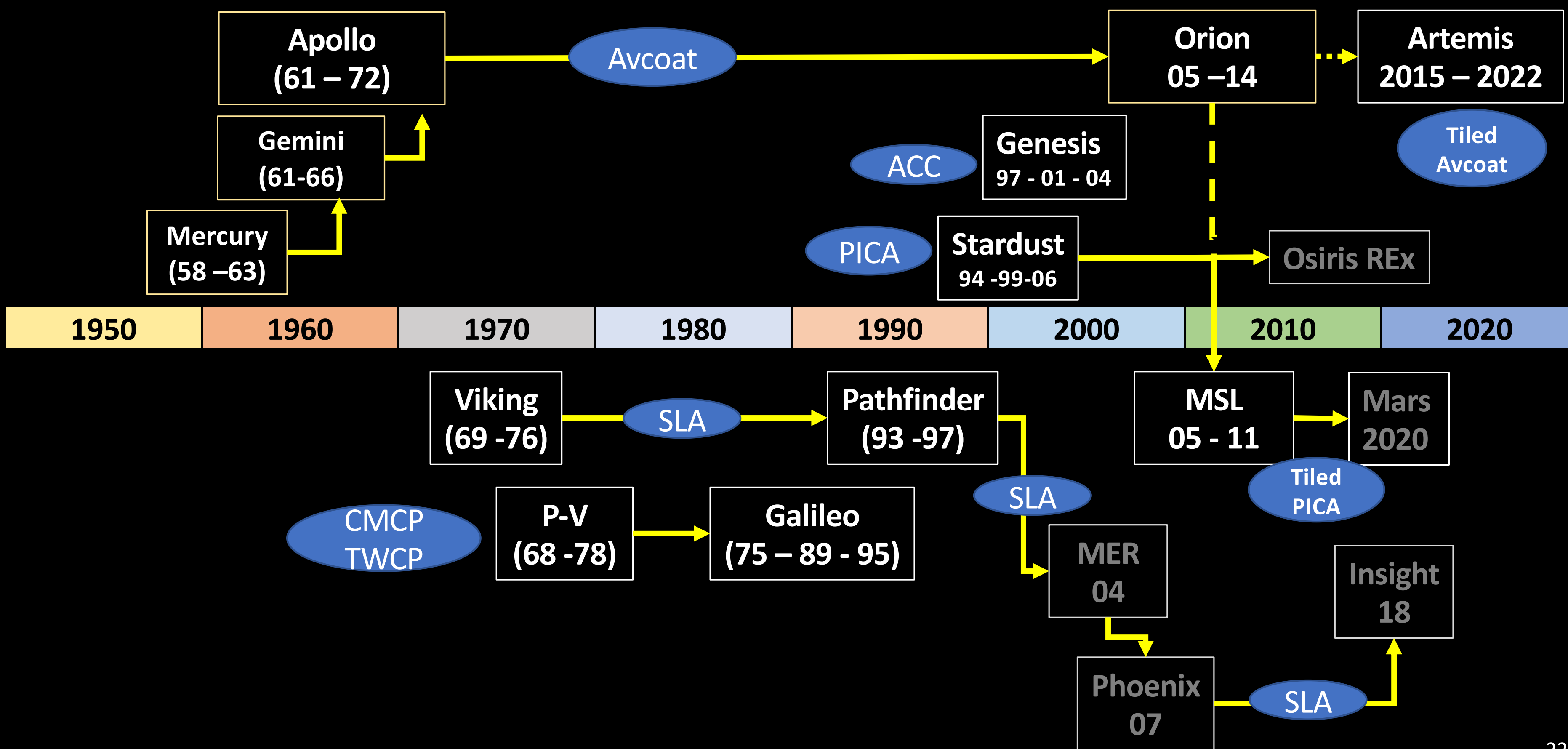
Posted on November 5, 2014 by Stephen Clark

Rationale:

- Improved production and schedule
- Improved manufacturing operations and design integration.
- Improved heat shield thermo-structural capability
- Reduced cost
- **Molded blocks** instead of honeycomb
  - Same ablator (Avcoat™ 5026-39)
  - RTV seams tested and verified
  - **~ 300 Avcoat™ blocks** bonded to the carrier structure
    - Compared to 300,000 cells for Honeycomb system
- **Compression Pad** (6 => 4)
  - 3-D MAT instead of Carbon Phenolic shingles

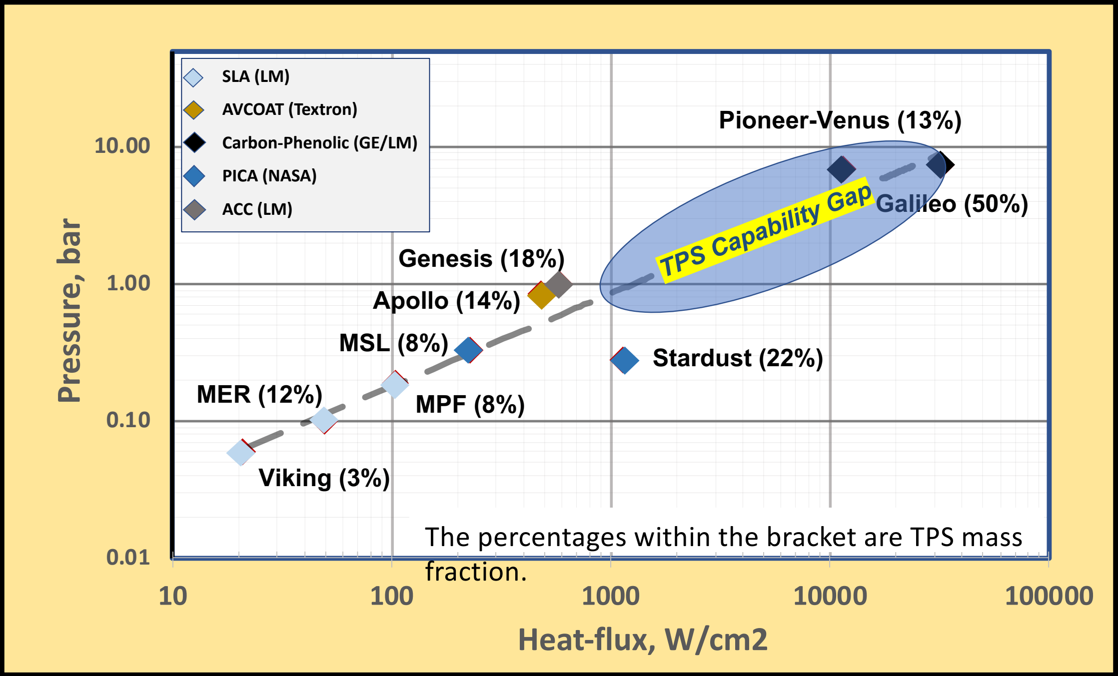


State-of-the-Art TPS (2020)



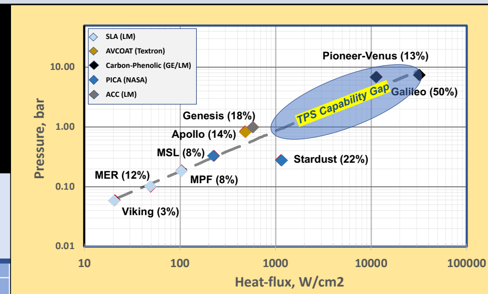
SOA TPS and Carbon-Phenolic Atrophy (early 2000's)

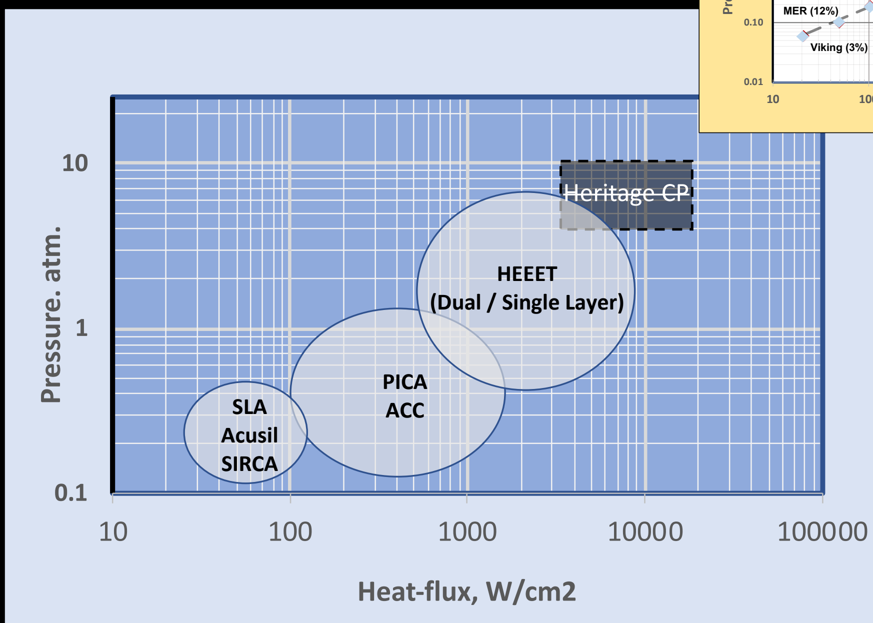
Atrophy of Carbon Phenolic and Its Impact to NASA missions

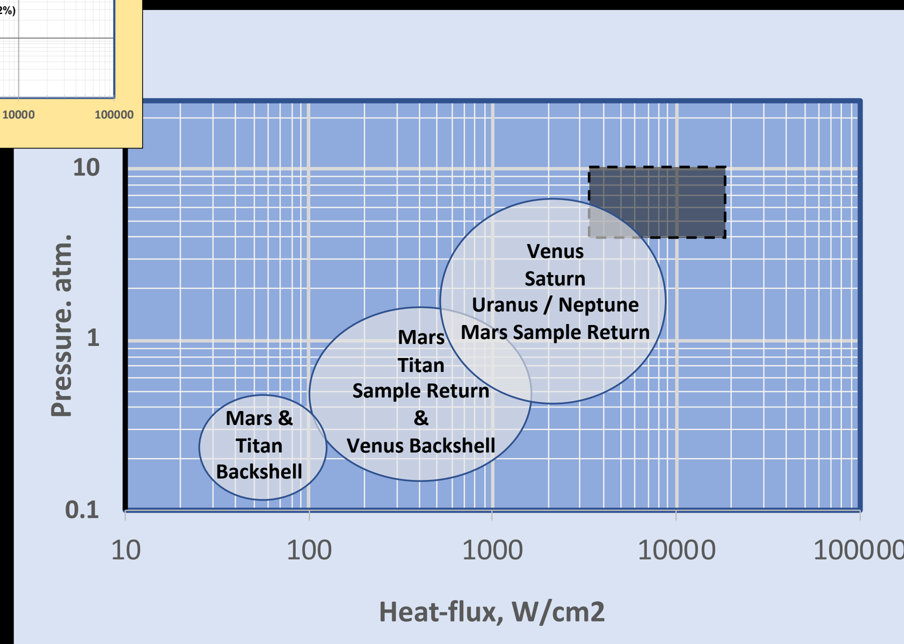


- NASA discovered in the early 2000's that heritage Carbon-Phenolic was no longer viable
  - The heritage rayon no longer manufactured and the expertise / processes to manufacture chop-molded carbon-phenolic is no longer maintained.
- In 2010 NASA decided to invest in alternate manufacturing (3-D Woven)

Investment in 3-D Woven TPS: Anticipation of Missions in the Coming Decades





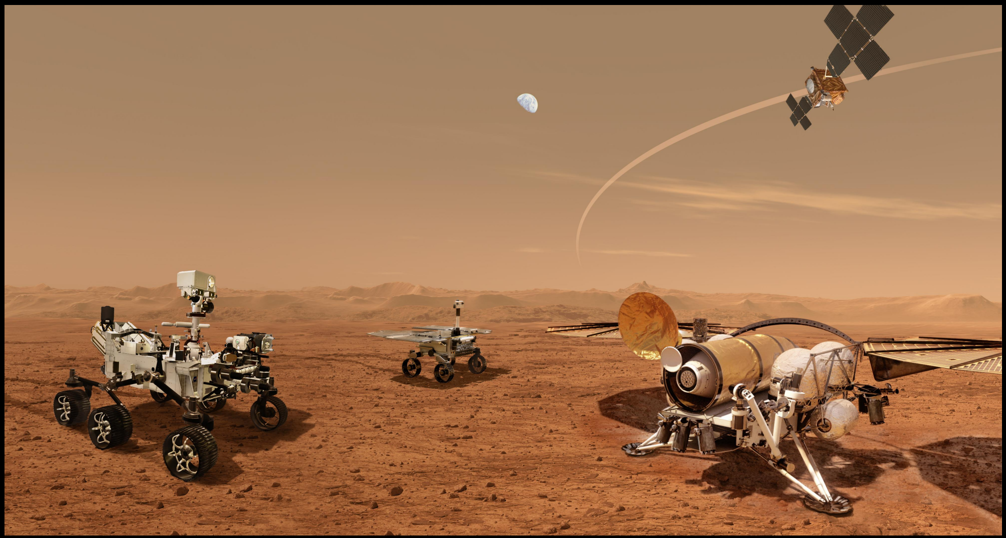


More on 3-D Woven TPS, in the afternoon presentations

Missions and TPS (2020 – 2030) – Mars Sample Return

Delivered to Mars surface:

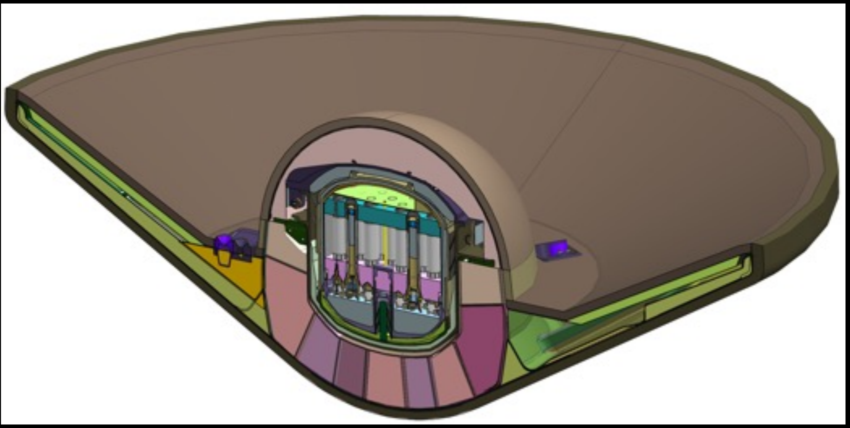
- A Fetch Rover and a Mars Ascent Vehicle with a Sample Container *(separate orbiter rendezvous with sample, puts it in the Earth Entry system, and brings it back towards Earth)*
- Current architecture (under development) is to use 2 Aeroshells of Mars 2020 class
- Baseline is tiled PICA heatshield
- Entry conditions anticipated to be well within PICA capability



Missions and TPS (2020 – 2030): MSR Earth Entry System

Earth Entry System (Sample Return Capsule)

- Stringent requirements due to backward planetary protection
- Aeroshell needs to be MMOD impact tolerant
- Steep entry to ensure smallest impact landing footprint – high entry environment
- No parachute; heatshield remains attached
- Impact attenuation design to withstand direct impact loads with the heatshield



Heat Shield: 3-D Woven TPS

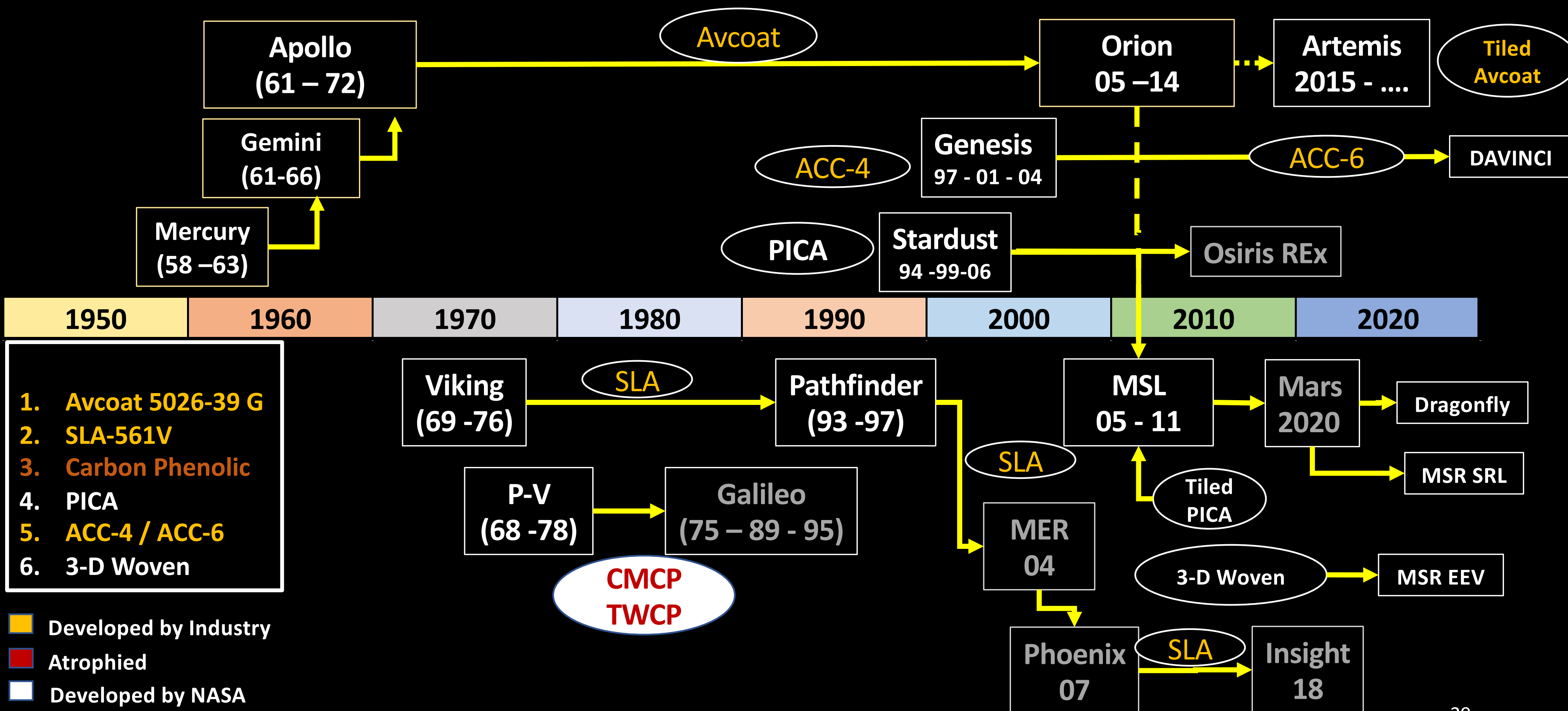
Missions and TPS (2020 – 2030): Dragonfly

- Mission to Titan
  - Launch 2027
  - Aeroshell ~ 4.5m diameter will carry and deliver a Quadcopter
  - Entry peak heat flux < 400 W/cm2
  - Heatshield TPS: Tiled PICA similar to MSL/Mars2020

Missions and TPS (2020 – 2030) – DAVINCI

- Venus Orbiter and Probe Mission (Launch 2029)
  - Aeroshell Size ~ 2.4 m
  - Entry Velocity ~ 10 km/s
  - Entry Peak heat-flux < 1200 W/cm2
  - Heatshield TPS based on Genesis
  - Advanced Carbon-Carbon (ACC-6) with insulation (Carbon FiberForm^{TM})

Ablators – State of the Art



NASA's Outlook for Missions in the 2030's and Beyond

- Human exploration of Moon
- Saturn Probes and Ice Giant Orbiter and Probe(s)
- Low-cost Mars Robotic Sample Return from
- Venus Lander, Aerial Platforms and Sample Return
- Human Missions to Mars

Summary

- NASA's missions have spanned low to extreme entry environments, with vehicles at a variety of scales
  - TPS for planetary as well as human missions have been NASA-unique
  - Future missions of interest to NASA may fall under two categories
    - Some commonality with commercial and others very much NASA unique
- NASA has not always chosen to maintain TPS capability
  - Atrophy has impacted NASA missions
  - Cost and time to recover can be substantial
- Commercial uses will most likely have a different objective function: Cost